NIST-GCR-89-560

Fire Propagation in Concurrent Flows

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August 1988

Issued February 1989

Prepared for
U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
Center for Fire Research
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ABSTRACT

The research tasks completed during this reporting period include an experimental study of the effect on the spread of flames of the turbulence intensity of an opposed air flow, and a theoretical analysis of the concurrent spread of flames over thin fuels. Both studies are in our opinion important contributions in the study of the fame spread process. The results of the experimental study show that the flame spread process is significantly affected by the flow turbulence intensity for flames spreading over both thin and thick fuels. For a fixed flow velocity, the spread rate decreases as the turbulent intensity is increased. This appears to be due to the turbulent convective cooling of the fuel surface and gas in the vicinity of the flame front. Also observed is that extinction of the flames occurs at lower velocities as the turbulent intensity increases. The results of the theoretical analysis, which are in good agreement with previous experimental measurements, give detailed information about the flame structure and mechanisms of flame spread. It is shown that the flame length and consequently the rate of flame spread, are strongly dependent on the interaction between the pyrolysis and burn-out fronts.

FIRE PROPAGATION IN CONCURRENT FLOWS

NBS Grant No. 60NANB7D0737

Final Progress Report

August 1, 1987 - July 31, 1988

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August 1988

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1. INTRODUCTION

The research performed during this reporting period forms part of an on-going research program aimed at the study of the mechanisms controlling the spread of fire in the presence of a forced flow of air, or other oxidizing gas. The oxidizing flow interacts with the fire and therefore affects its rate of spread. The final objective of the research program is to provide information about the spread of fire that can be used in the development of models of fire growth in rooms and of test methods of the flammability of materials.

The tasks conducted during this period include experimental observations of the effect on the opposed flow flame spread of the flow turbulence intensity, and numerical modeling of the concurrent spread of flames over thin fuels. We feel that both works are important contributions in the study of the flame spread process.

In most practical cases the spread of fire occurs under turbulent flow conditions. Flow turbulence can affect both the heat transfer and the chemical kinetic mechanisms that control the flame spread process, both by convective cooling and gas mixing. The determination of the role of these mechanisms is necessary to understand and predict the spread of fire under realistic conditions. With the exception of the works of Orloff, et al. (15th Int. Symp. Comb. p. 183, 1975) and Saito and co-workers (1st Int. Symp. Fire Safety, p. 75, 1986; 24th Nat. Heat Trans. Conf. 1987) for the upward turbulent spread of flames, no systematic experiments have been performed to date to determine the effect of turbulence on the flame spread process. This is the objective of this work. The work consists of a parametric study where the velocity and turbulence intensity of an air flow are varied to study their effect on the rate of flame spread over thick and thin fuels.

With regard to the theoretical task reported here, very few analyses have been published to date of the concurrent spread of flames over a thin combustible. The works of Markstein and de Ris (14th Int. Symp. Comb. p. 1085, 1973) and Fernandez-Pello (Comb. Flame, 31, p. 135, 1978; Comb. Flame, 36, p. 63, 1979) provide only approximate analytical solutions of the problem, which can only describe partially the experimental observations. The present work provides a more accurate description of the process by removing some of the critical assumptions made in previous analyses. The results describe and agree well with the experimental observations.

In the following section a summary is provided of the above studies. Papers prepared for publication describing these studies are included in this report in the form of appendices.

II. RESEARCH PROGRESS

II.1 Experiments of Flame Spread in an Opposed Turbulent Flow

An experimental study has been conducted of the influence on the spread of flames over the surface of thick and thin solid combustibles of the turbulence intensity of an air flow opposing the direction of flame propagation. The experiments are conducted in a facility specifically designed to perform flame spread experiments consisting of a small scale combustion tunnel and supporting instrumentation based primarily on optical and thermocouple measuring methods. The turbulence intensity in the tunnel test section is varied by means of grids and perforated plates of different sizes placed at the exit of the tunnel converging nozzle. The velocity and turbulence intensity of the flow field are measured with a one component Laser Doppler Velocimeter. The flame spread rate is obtained visually timing the pass of the flame front through marks placed at fixed distances along the combustible surface.

II.1.1 Thick PMMA Sheets

The measurements of the flame spread rate over PMMA sheets as a function of the opposed air flow velocity are shown in Fig. 1 for several values of the turbulence intensity. It is seen that the spread rate first increases sharply as the flow velocity is increased and then decreases. The initial increase appears to be the result of a transition from a mixed flow type flame spread to a forced flow one. At low flow velocities, normal buoyancy tends to lift the flame from the fuel surface, which results in reduced heat transfer from flame to fuel and consequently in a slower spread rate. The decrease of the flame spread rate with the opposed flow velocity at higher air velocities is the result of gas phase chemical kinetics effects. As the opposed flow velocity increases the residence time of the fuel vapor/air mixture ahead of the flame decreases. For constant chemical time this results in a slowdown of the combustion reaction at the flame leading edge that sustain the propagation of the flame. This effect is observed to occur at all turbulence intensity levels.

The effect of turbulence intensity on the flame spread rate can also be deduced from the results of Fig. 1. This is presented in Fig. 2 for three value of the flow velocity. It is seen that for all flow velocities the flame spread rate first increases and then decreases as the turbulent intensity increases. The maximum occurs at approximately 6% of the turbulent intensity. This result may reflect the differences in the boundary layer that take place during the transition from laminar to turbulent flow. For PMMA, heat conduction through the solid is an important flame spread mechanism. Thus, the thinning of the boundary layer that occurs as the flow changes from laminar to turbulent should result in an increase of the flame spread rate because the heat transfer to the

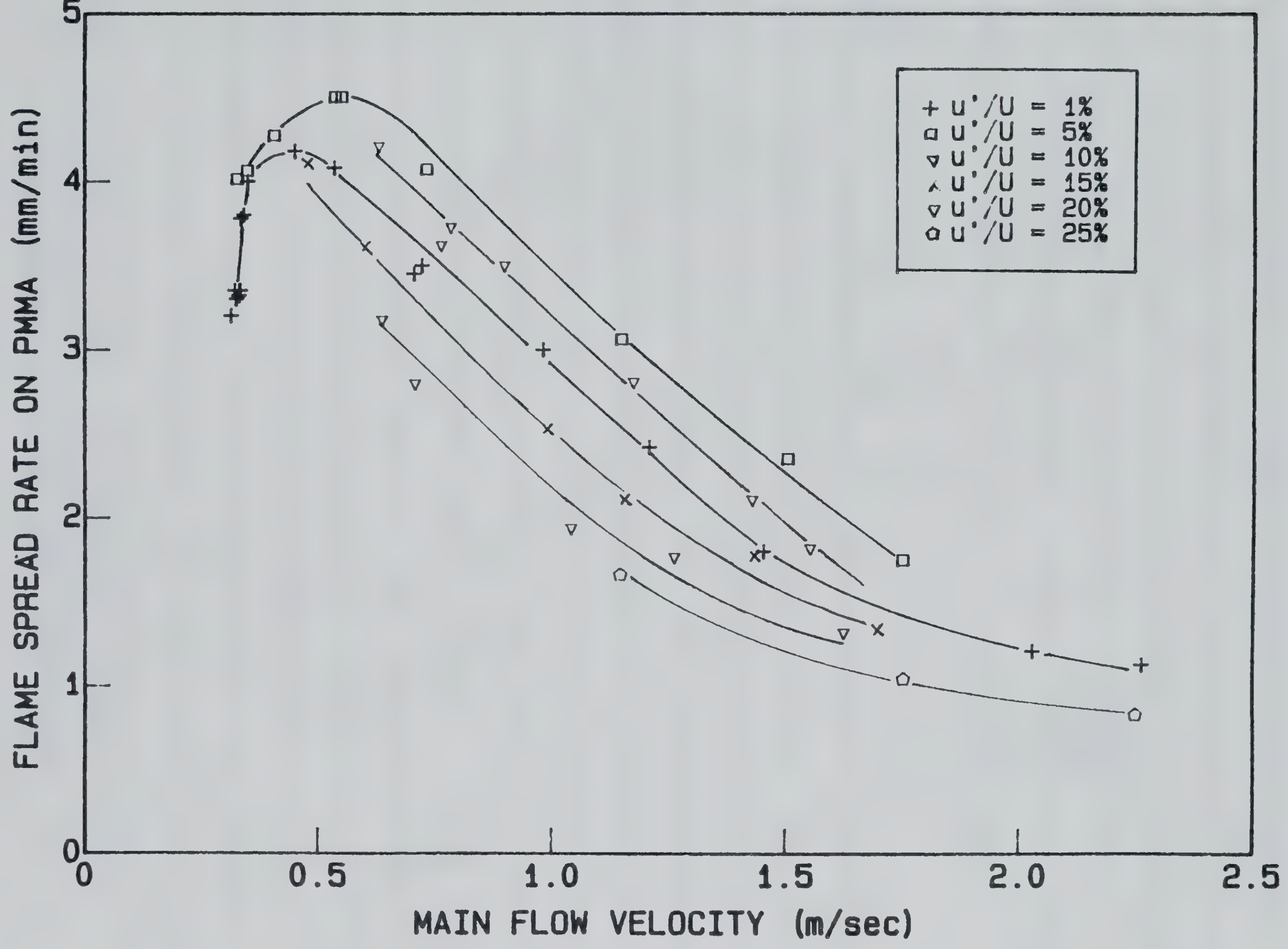
FLAME SPREAD RATE ON PMMA (mm/min)
MAIN FLOW VELOCITY (m/sec)
0
1
2
3
4
5
0
0.5
1.0
1.5
2.0
2.5
+ u'/U = 1%
□ u'/U = 5%
▽ u'/U = 10%
x u'/U = 15%
▽ u'/U = 20%
⬠ u'/U = 25%

FIGURE 1.

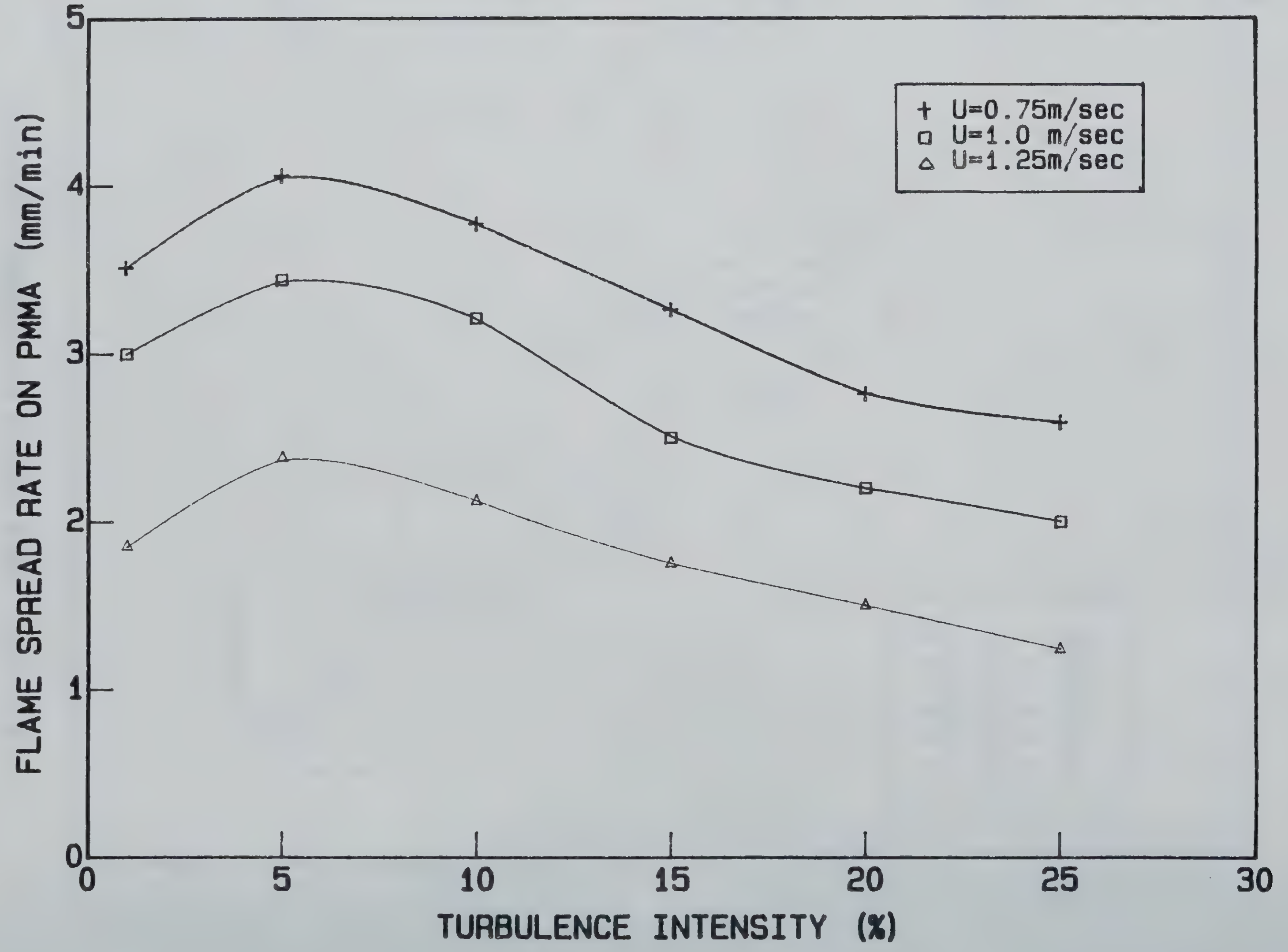
+ U=0.75m/sec
□ U=1.0 m/sec
△ U=1.25m/sec
FLAME SPREAD RATE ON PMMA (mm/min)
0
1
2
3
4
5
TURBULENCE INTENSITY (%)
0
5
10
15
20
25
30

FIGURE 2.

solid increases. At low turbulence intensities this effect appears to be more important than the potential enhancement of the fuel convective cooling that should occur as the flow becomes more turbulent. Another possible mechanism that should be considered is an enhancement by the flow turbulence of the fuel vapor and air mixing at the flame leading edge, which could result in a stronger gas phase reaction and consequently in a faster flame spreading velocity. Although we think that the former mechanism is the more likely to occur, there is not enough available information at this point to resolve the issue.

II.1.2 Thin Paper Sheets

The results of the measurements of the variation with the air flow velocity and turbulence intensity of the flame spread rate over thin paper sheets are presented in Fig. 3. In this case, the flames do not propagate (extinguish) in gas flows with velocities larger than 1.5 m/s. The low flow velocities at which the tests had to be conducted limited the maximum range of turbulence intensities attainable to 15%. From the results of Fig. 3 it is seen that for all turbulence intensities the spread rate decreases as the opposed gas velocity increases. The decrease in the low velocity region, however, is small. This again appears to be the influence of buoyancy on the flame spread process at low flow velocities. This influence is not as noticeable as in the case of PMMA probably because with paper the flames are smaller and consequently less buoyant. The stronger decrease of the flame spread rate with the flow velocity observed for the larger air velocities appear to be the combined effect of convective cooling and weakening of the chemical reaction (smaller residence time) that take place as the opposed flow velocity increases.

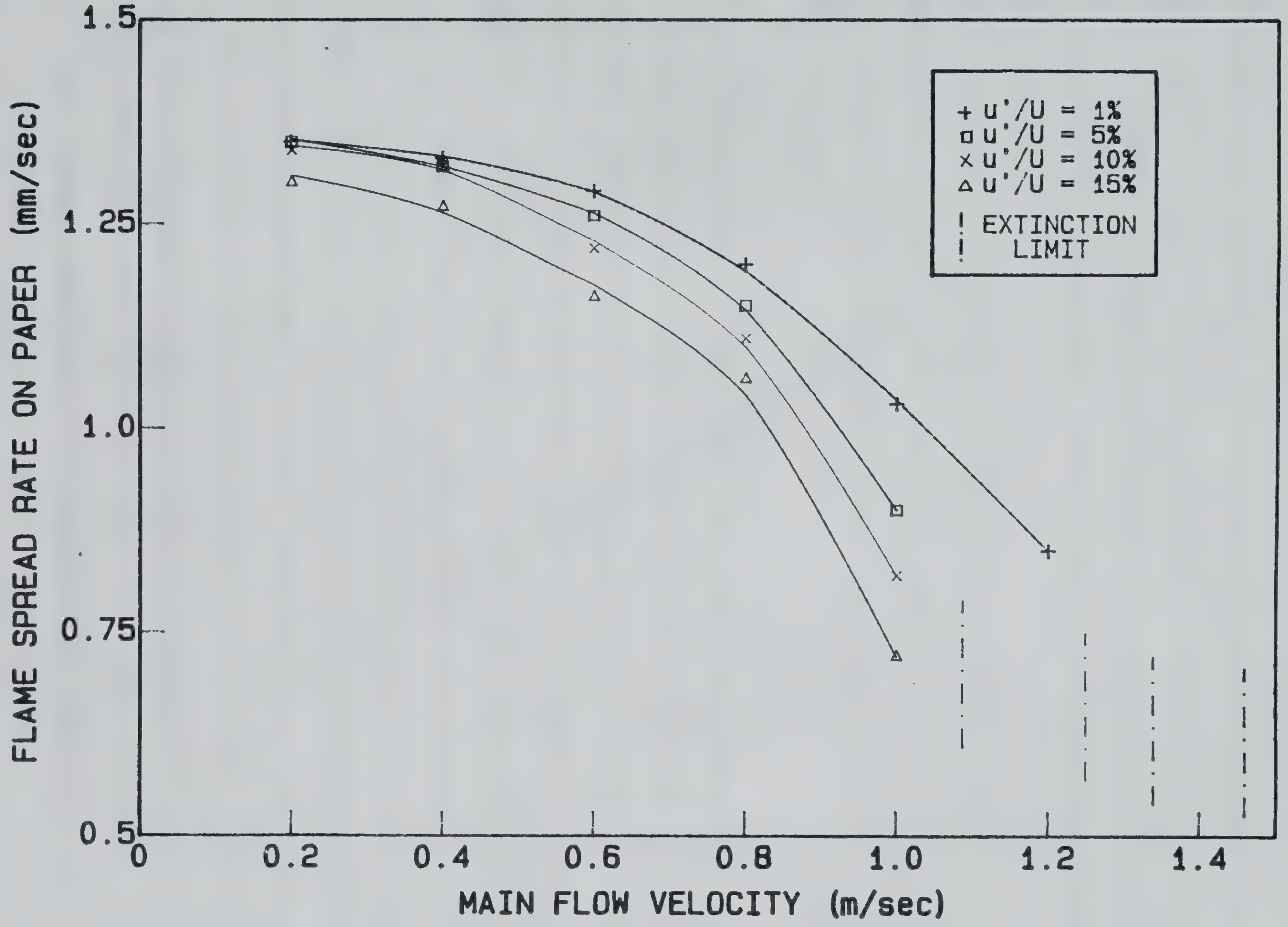
1.5
1.25
1.0
0.75
0.5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
FLAME SPREAD RATE ON PAPER (mm/sec)
MAIN FLOW VELOCITY (m/sec)
+ u'/U = 1%
□ u'/U = 5%
× u'/U = 10%
△ u'/U = 15%
¦ EXTINCTION LIMIT

FIGURE 3.

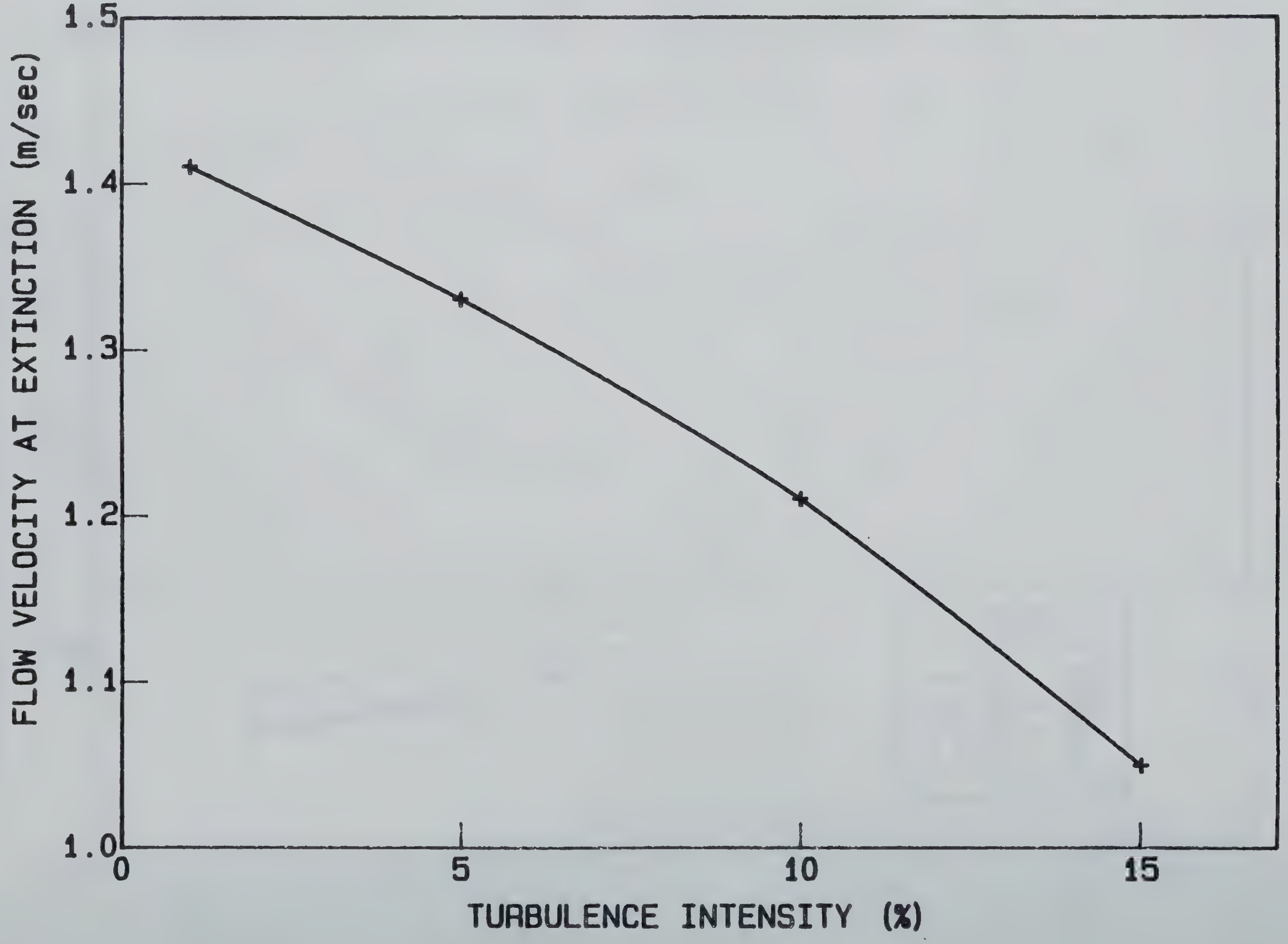
1.5
1.4
1.3
1.2
1.1
1.0
FLOW VELOCITY AT EXTINCTION (m/sec)
0
5
10
15
TURBULENCE INTENSITY (%)

FIGURE 4

An interesting result obtained in these experiments is the effect of flow turbulence intensity on the extinction of the flame. This is shown in Fig. 4 where the gas velocity at which extinction is observed is presented as a function of the turbulence intensity. It is seen that flame extinction occurs at lower flow velocities when the turbulence intensity is increased. This result, although it is in general agreement with the other flame spread results, is somewhat unexpected since turbulence is often viewed as a means to enhance fuel combustion processes.

A paper reporting this result will be presented at the 1988 Fall Meeting/Western States Section of the Combustion Institute. It will also be submitted for publication in Combustion and Flame. The paper is included in this report as Appendix A.

II.2 Model of Concurrent Flame Spread Over a Thin Charring Solid

A theoretical model has been developed of the spread of a flame over the surface of a thin combustible solid in a gas flow moving in the direction of flame propagation. The combustion reaction and the solid pyrolysis are modeled respectively with a one-step, second order, and with a zero order Arrhenius reaction. The charring of the solid is modeled by treating the solid as a two component material, the combustible component that gasifies, and the char that remains occupying the initial solid volume. To simplify the mathematical solution of the problem, a Hagen-Poiseuille flow is prescribed, thus eliminating the need for using the momentum conservation equations. The transient, reactive, gas phase balance equations of energy and species coupled at the interface to the solid phase energy equation are solved numerically to describe the evolution of the flame and soot properties, and through them to predict the variation with time of the flame, pyrolysis and burnout distances and their dependence on the flow velocity.

The model is applied to the description of the spread of flames over paper sheets in a concurrent air flow. In Fig. 5 the predicted variation with time of the flame, pyrolysis and burnout distances are presented for several flow velocities. The experimental data of Loh and Fernandez-Pello (1stl Int. Symp. Fire Saf. Sci., 65, 1986) are included for comparison. In Fig. 6 the predicted dependence on the flow velocity of the steady state pyrolysis spread rate is also presented with the comparison with the experiments. It is seen that the predictions of the model agree well with the experiments. Particularly important is the description of the transition of the flame spread process from an initial accelerative stage to a final steady state. The transition is determined by the interaction between the progress of the pyrolysis and the burn-out fronts, and their effects in the flame length. According to boundary layer analyses, the model predicts a spread rate that increases, although weakly, with the flow velocity, while the experiments show a spread rate that first increases at low flow velocities and then becomes constant as the flow velocity is increased. Some reasons for this potential disagreement are discussed in the work. Finally the predicted flame extinction limit due to increased concurrent velocity is very close to the experimentally determined value.

This work was performed in collaboration with Dr. Di Blasi of Naples University, Italy. A paper reporting the results has been accepted for publication at the Proceedings of the 22nd Symposium International on Combustion, held in Seattle, Washington, August 1988. It is included in this report as Appendix B.

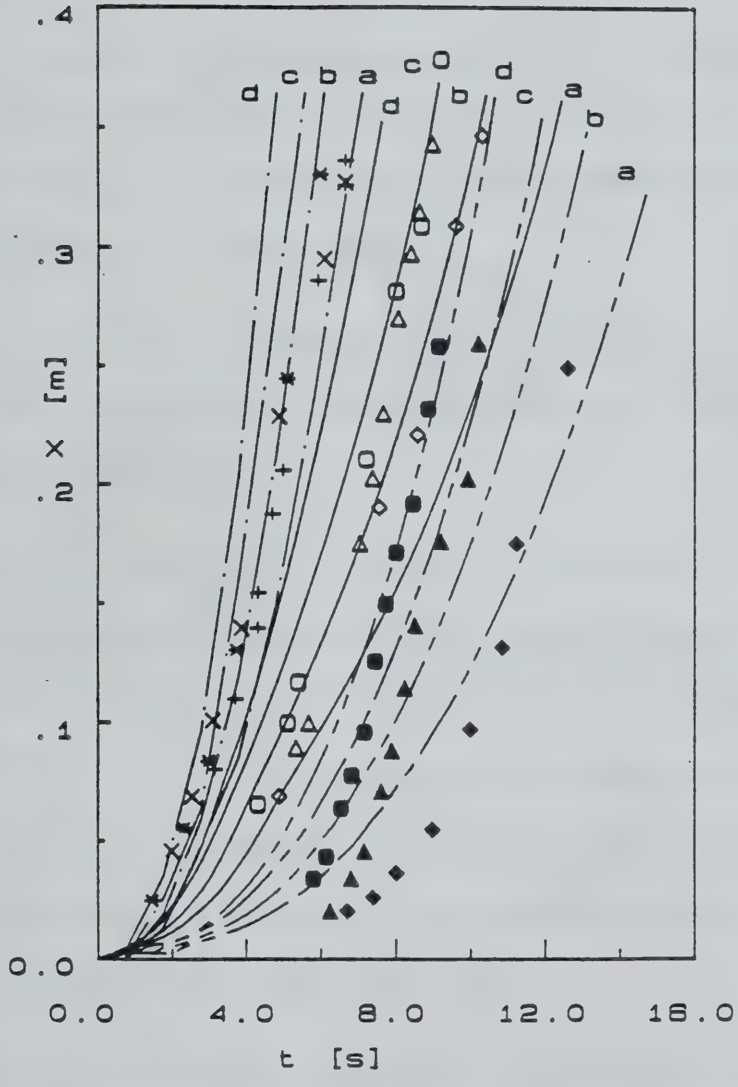

FIGURE 5.

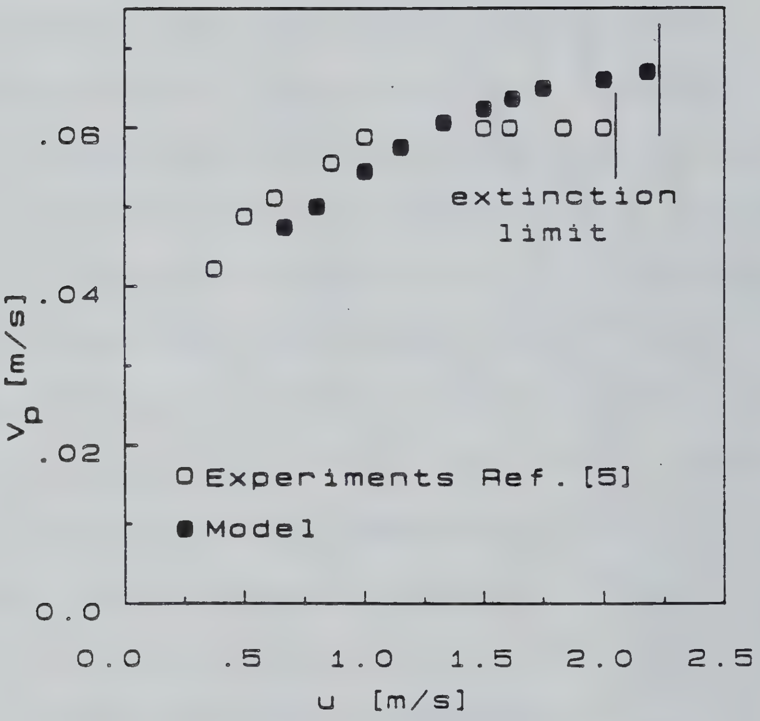
.06
.04
.02
0.0
V_p [m/s]
0.0
.5
1.0
1.5
2.0
2.5
u [m/s]
extinction
limit
○ Experiments Ref. [5]
● Model

FIGURE 6.

II.3 Publications and Presentations

Kodama, H., Miyasaka, K. and Fernandez-Pello, A.C., "Extinction and Stabilization of a Diffusion Flame on a Flat Combustible Surface with Emphasis on Thermal Controlling Mechanisms," Combustion Science and Technology, 94, 1-6, pp. 37-50 (1987).

Amos, B., Kodama, H. and Fernandez-Pello, A.C., "An Analysis of the Ignition by Vapor Radiation Absorption of Vaporizing Fuel at Zero Gravity," presented at the AIAA 25th Aero. Sci. Meeting, Reno, Nevada, 1987. Also Progress in Aeronautics and Astronautics (in press), 1988.

Amos, B., "Ignition and Flame Propagation Studies Over a Flat Fuel Surface," Ph.D. Thesis, Department of Mechanical Engineering, University of California, Berkeley, August 1987.

Di Blasi, C., Cresticelli, S., Russo, G. and Fernandez-Pello, A.C., "Predictions of the Dependence on the Opposed Flow Characteristics of the Flame Spread Rate Over Thick Solid Fuels," 2nd Int. Symp. of Fire Safety Sci., (accepted) Japan, June 1988.

Amos, B. and Fernandez-Pello, A.C., "Ignition and Flame Development of a Vaporizing Conmbustible Surface in a Stagnation Point Flow," submitted to Combustion Science and Technology (1988).

Di Blasi, C., Cresticelli, S., Russo, G. and Fernandez-Pello, A.C., "Model of the Flow Assisted Spread of Flames Over a Thin Charring Combustible," 22nd Symposium (Int.) in Combustion (accepted), Seattle, WA, August 1988.

Zhou, L., Fernandez-Pello, A.C. and Cheng, R., "Flame Spread in an Opposed Turbulent Flow," submitted for publication in Combustion and Flame (1988).

Fernandez-Pello, A.C., "Controlling Mechanisms of Flame Spread," presentation given at Naples University, Italy, November 1987, and at Sydney University, Australia, June 1988.

APPENDIX A

FLAME SPREAD IN AN OPPOSED TURBULENT FLOW

by

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Presented at the 1988 Fall Technical
Meeting/Western Section of the Combustion
Institute, Laguna Beach, CA, October 17-18, 1988

ABSTRACT

An experimental study is presented of the influence on the spread of flames over the surface of a solid combustible of the turbulence intensity of a gas flow opposing the direction of flame propagation. In the study, the flow velocity and its turbulent intensity are varied to observe the effect of these flow parameters on the rate of flame spread over thick PMMA and thin filter paper sheets. Also observed is their effect on the extinction of the flame. The results show that for thick PMMA sheets the spread rate first increases and then decreases as the turbulent intensity is increased. The presence of a maximum appears to be the result of the flow transition from laminar to turbulent that influences the heat transfer process from flame to fuel. Through interferometric photographs it is shown that the decrease of the spread rate with the turbulence intensity is primarily due to the convective cooling of the region near the flame front. For thin paper sheets the spread rate always decreases as the turbulence increases. The observed differences between the thick PMMA and the thin paper results are probably due to their different mechanism of heat transfer ahead of the flame. It is also found that extinction of the flame occurs at lower flow velocities for higher turbulence intensities. This result, which is unexpected, suggests that convective cooling and/or flame stretch, and no turbulent mixing, are the major effects of the flow turbulence on the extinction of a spreading flame.

INTRODUCTION

In most practical cases the spread of fire occurs under turbulent flow conditions. Flow turbulence can affect both the heat transfer and chemical kinetics mechanisms that control the flame spread process. In opposed flow flame spread, turbulence could produce an increased convective cooling of the unburnt fuel surface and gas region ahead of the flame. Also, it could increase the conductive heating of the solid due to the enhanced heat transfer in the burning region. The former effect should result in a decrease of the flame spread rate as the flow turbulence increases. The latter in an increase. Similarly, turbulence mixing could affect the flame spread process by either favoring the mixing of fuel vapor and oxidant and thus enhancing the combustion reaction, or by diluting the fuel vapor mixture with oxidant which could weaken the reaction. Determination of the role of these different mechanisms is necessary to understand and predict the turbulent spread of fire.

With the exception of the work of Orloff et al, [1] for upward turbulent flame spread over large PMMA sheets, and of Saito and co-workers [2,3] for upward turbulent spread of flames over PMMA and wood sheets, no systematic experiments have been performed to date to determine the effect of turbulence on the flame spread process. This is the objective of this work. The work consists of a parametric study of the spread of flames over thick and thin fuels in a turbulent air flow opposing the direction of propagation. The parameters varied are the flow velocity and its turbulence intensity. The effect of these parameters on the rate of flame spread and on the flame extinction is reported.

Experimental Installation and Procedure

The experimental apparatus consists of a small scale combustion tunnel, designed to conduct combustion experiments under varied flow conditions, and the supporting instrumentation, based primarily on optical and thermocouple measuring methods. A schematic diagram of the installation is shown in Fig. 1. The tunnel has a settling chamber 0.89 m long with a square cross section 0.3 m by 0.18 m, that is connected to the tunnel test section by a converging nozzle with a reduction area of 5.5 to 1 in 0.3 m. The tunnel test section is 0.6 m long and has a rectangular cross section 13 mm wide and 76 mm high. The side walls are made of 6 mm Pyrex glass, and the floor and ceiling sides are made of 25.4 mm thick Marinite sheet. The tunnel is mounted horizontally on a three axis positioning table. The positioning of the table is accomplished with lead screws actuated with computer controlled stepping motors. The system permits positioning the test section with respect to the stationary optical instrumentation at 0.1 mm spacing.

For the thick fuel experiments the specimen is mounted flush in the Marinite floor with its upstream edge placed 15 mm from the exit of the tunnel convergent nozzle. In the present work the fuel specimens are 12.7 mm thick PMMA (Rohm and Mass, Plexiglas G) sheets, 76 mm wide by 0.3 m long. The thin fuel specimens are 0.33 mm thick Whatman filter paper, 76 mm wide by 0.3 m long. The paper sheets are mounted in a metallic frame by inserting them in metallic spikes placed on the sides of the frame [4]. The paper is positioned in the middle of the test section to permit unrestricted burning over both surfaces. The paper sheets are dried in an oven for twenty-four hours prior to their use in the experiments.

The gas flow in the tunnel is supplied either from centralized compressed air or from bottles of compressed oxygen and nitrogen. The individual flow rates are controlled and measured with critical nozzles. Turbulence is generated by means of grids, or perforated plates, placed at the exit of the tunnel converging nozzle. A prescribed turbulence intensity is obtained through a combination of flow velocity and plate blockage ratio. As a consequence high turbulence intensity could not be obtained at very low flow velocities. The distribution of turbulence intensity through the test section is characterized by an initial region, approximately 40 mm where the turbulence decays sharply, followed by a 0.2 m region of practically constant turbulence, and a final region where the turbulence decays again due to entrainment effects at the test section exit. The gas velocity and turbulence intensity are measured with a one component LDV (TSI) operating in the forward scattered mode. The laser source is a Spectra Physics Ar.-Ion laser with a 2 W total output power. The signal is processed with a TSI Doppler processor and transferred to a micro-computer (IBM/AT).

The experimental installation also includes a laser interferometric system that can be operated either as a Mach-Zehnder Interferometer or as a Holographic Interferometer. In this work the former arrangement was used to provide qualitative information about the effect of the flow turbulence on the flame and thermal layer structure. In addition to the interferometer, the installation contains a thermocouple based set-up for gas and solid phase temperature measurements.

The rate of flame spread is measured by timing visually the pass of the flame over previously ruled marks on the fuel surface. For PMMA sheets the flame spread process is initiated by igniting the top downstream edge of the sheet with a propane torch. The filter paper sheets are ignited with an electrically heated nichrome wire placed in close contact with the paper at its downstream edge.

RESULTS

1. Thick PMMA sheets.

The measurements of the flame spread rate over PMMA sheets as a function of the opposed air flow velocity are shown in Fig. 2 for several values of the turbulence intensity. Because of the difficulty of producing high turbulence intensity at low flow velocities, no data was taken at those conditions. The data correspond to averages of three different tests. The spread rate was measured in the test section region that has an approximately constant turbulence intensity.

The results of Fig. 2 for low turbulence intensity show that the spread rate first increases sharply as the flow velocity is increased and then decreases. The initial increase appears to be the result of a transition from a mixed flow type flame spread to a forced flow one. At low flow velocities, normal buoyancy tends to lift the flame from the fuel surface, which results in reduced heat transfer from flame to fuel and consequently in a slower spread rate. The effect of buoyancy on the flame and thermal layer location can be observed by comparing the interferograms shown in Fig. 3 for flow velocities of 0.2 and 0.5 m/sec. It is seen that for 0.5 m/sec the thermal layer is thinner, and the flame slightly closer to the surface, than for 0.2 m/sec, which confirms the above argument. The decrease of the flame spread rate with the opposed flow velocity at higher air velocities is in agreement with the previous results of Fernandez-Pello et al. [5]. As inferred in that work, and later predicted theoretically, [6], the decrease is the result of gas phase chemical kinetics effects. As the opposed flow velocity increases the residence time of the fuel vapor/air mixture ahead of the flame decreases. For constant chemical time this results in a slow down of the combustion reaction at the flame leading edge that sustain the propagation of the flame. This effect is observed to occur at all turbulence intensity levels. At flow velocities larger than 2 m/s the flame spread rate is so slow that the PMMA surface recedes, producing a stagnation region that acts as a flame holder. Thus, for gas velocities larger than 2 m/s the flame propagation is really a mass burning process rather than a flame spread process and is not considered here.

The effect of turbulence intensity on the flame spread rate can also be deduced from the results of Fig. 2. This is presented in Fig. 4 for three value of the flow velocity. It is seen that for all flow velocities the flame spread rate first increases and then decreases as the turbulent intensity increases. The maximum occurs at approximately 6% of the turbulence intensity. This result may reflect the differences in the boundary layer that take place during the transition from laminar to turbulent flow (Fig. 5). For PMMA, heat conduction through the solid is an important flame spread mechanism [7]. Thus, the thinning of the boundary layer that occurs as the flow changes from laminar to turbulent should result in an increase of the flame spread rate because the heat transfer to the solid increases. At low turbulence intensities this effect appears to be more important than the potential enhancement of the fuel convective cooling that should occur as the flow becomes more turbulent. Another possible mechanism that should be considered is an enhancement by the flow turbulence of the fuel vapor and air mixing at the flame leading edge, which could result in a stronger gas phase reaction and consequently in a faster flame spreading velocity. Although we think that the former mechanism is the more likely to occur, there is not enough available information at this point to resolve the issue.

The results of Figs. 2 and 4 also show that once in the turbulent flow regime, the flame spread rate decreases as the turbulent intensity increases.

This effect seems to be the result of convective cooling of the fuel surface and gas at the region in the vicinity of the flame leading edge. The sequence of interferograms of Fig. 5 shows this clearly. It is seen that as the turbulence intensity is increased the thermal layer fluctuates strongly, sometimes becoming very thin near the flame front. This indicates the inducement by the turbulent eddies of cold air from the free stream toward the fuel surface, which results in both a cooling of the fuel surface and of the gas phase chemical reaction. Both are effects that tend to decrease the rate of flame spread.

2. Thin paper sheets

The results of the measurements of the variation with the air flow velocity and turbulence intensity of the flame spread rate over thin paper sheets are presented in Fig. 6. In this case, the flames do not propagate (extinguish) in gas flows with velocities larger than 1.5 m/s. The low flow velocities at which the tests had to be conducted limited the miximum range of turbulence intensities attainable to 15%. From the results of Fig. 6 it is seen that for all turbulence intensities the spread rate decreases as the opposed gas velocity increases. The decrease in the low velocity region, however, is small. This again appears to be the influence of buoyancy on the flame spread process at low flow velocities. This influence is not as noticeable as in the case of PMMA probably because with paper the flames are smaller and consequently less buoyant. The stronger decrease of the flame spread rate with the flow velocity observed for the larger air velocities is in agreement with the results of Fernandez-Pello et al. [5]. As it was discussed in that work, this appears to be the combined effect of convective cooling and weakening of the chemical reaction (smaller residence time) that take place as the opposed flow velocity increases.

The influence of the turbulence intensity on the flame spread rate is also deduced from the results of Fig. 6. It is seen that in this case the spread rate always decreases as the turbulence intensity increases, with no apparent difference during the transition from laminar to turbulent as observed with PMMA. This is possibly the result of the different mechanisms of heat transfer that control the spread of the flame for PMMA or paper. For thin paper sheets, heat transfer through the gas ahead of the flame is the dominant mechanism of heat transfer during the spread of the flame [7]. Thus, the thinning of the boundary layer during the transition from laminar to turbulent flow should have a secondary effect in comparison with the enhancement of the convective cooling caused by the flow turbulence. It is therefore understandable that for flames spreading over paper sheets the simple appearance of flow turbulence could result in a decrease of the spread rate due to both convective cooling of the gas and cooling of the gas phase chemical reaction.

An interesting result obtained in these experiments is the effect of flow turbulence intensity on the extinction of the flame. This is shown in Fig. 7 where the gas velocity at which extinction is observed is presented as a function of the turbulence intensity. It is seen that flame extinction occurs at lower flow velocities when the turbulence intensity is increased. This result, although it is in general agreement with the other flame spread results, is somewhat unexpected since turbulence is often viewed as a means to enhance fuel combustion processes. The fact that in this case the flow turbulence tends to facilitate the flame extinction indicates that convective cooling of the reaction zone, and/or flame stretching effects, are the dominant mechanisms in the flame extinction process, and that the enhancement of the fuel/air mixing by the turbulence has a secondary influence on the gas phase reaction.

CONCLUDING REMARKS

The detailed parametric study conducted in the present work of the spread of flames in an opposed turbulent flow has shown that turbulence intensity has a significant effect on the rate at which the flame spreads, and on the conditions leading to its extinction. The study has introduced a whole new aspect of the flame spread problem that is of special interest given the fact that most practical fires take place under turbulent flow conditions. The nature of the results indicate that the flow turbulence may affect both the heat transfer and the chemical kinetic mechanisms that control the spread of the flame. Although throughout this paper phenomenological arguments are given in an attempt to explain the different experimental observations, the data acquired is not sufficient to prove with certainty that the arguments are correct.

In order to fully understand the effect of turbulence on the flame spread process it appears that it may be necessary to study its influence in each one of the flame spread controlling mechanisms, individually. This could be done by conducting experiments under conditions where the flame spread process is controlled by only heat transfer effects (high oxygen concentration and low gas velocity) or by only gas phase chemical kinetic effects (low oxygen concentration and/or high flow velocity). Also important would be the identification of the non-dimensional parameters that control the turbulent flow flame spread process, and the subsequent correlation of the results in terms of these parameters.

Also interesting is the observation that an increase in the flow turbulence causes an earlier extinction of the spreading flame. The fact that this result is contrary to the more common observation that turbulence favors the combustion reaction by enhanced mixing suggests that the extinction of a spreading flame may be controlled by mechanisms that are somewhat different than those in free flames. The elucidation of this result deserves further attention.

ACKNOWLEDGEMENTS

The authors would like to thank Professor R. Bilger for his useful suggestions concerning the design of the combustion tunnel and the organization of the experiments. This work was supported by the National Bureau of Standards under Grant No. 60NANB7D0737.

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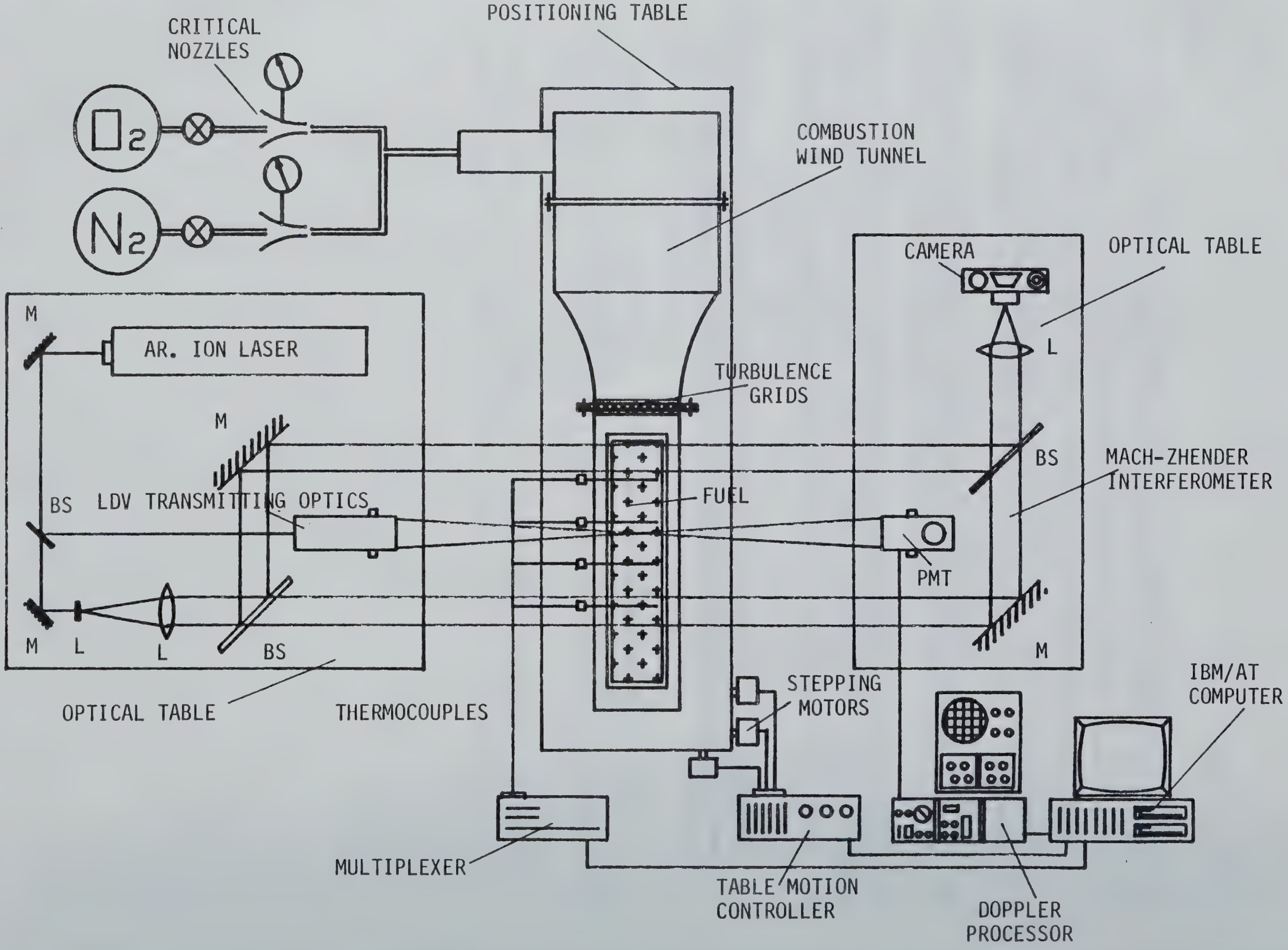

CRITICAL
NOZZLES
POSITIONING TABLE
O_2
N_2
COMBUSTION
WIND TUNNEL
CAMERA
OPTICAL TABLE
M
AR. ION LASER
L
TURBULENCE
GRIDS
M
BS
MACH-ZHENDER
INTERFEROMETER
BS
LDV TRANSMITTING OPTICS
FUEL
PMT
M
L
L
BS
M
OPTICAL TABLE
THERMOCOUPLES
STEPPING
MOTORS
IBM/AT
COMPUTER
MULTIPLEXER
TABLE MOTION
CONTROLLER
DOPPLER
PROCESSOR

Fig. 1

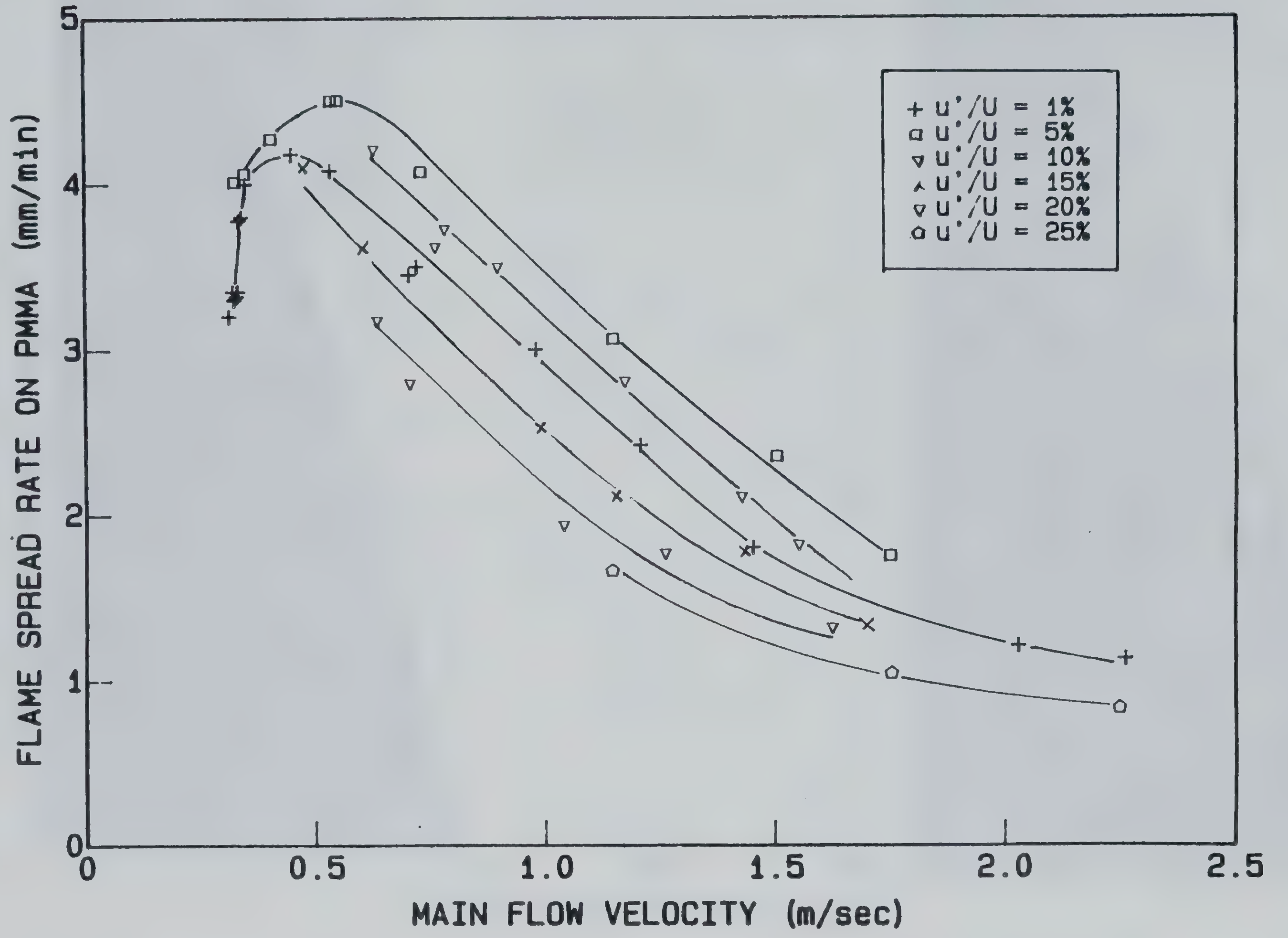
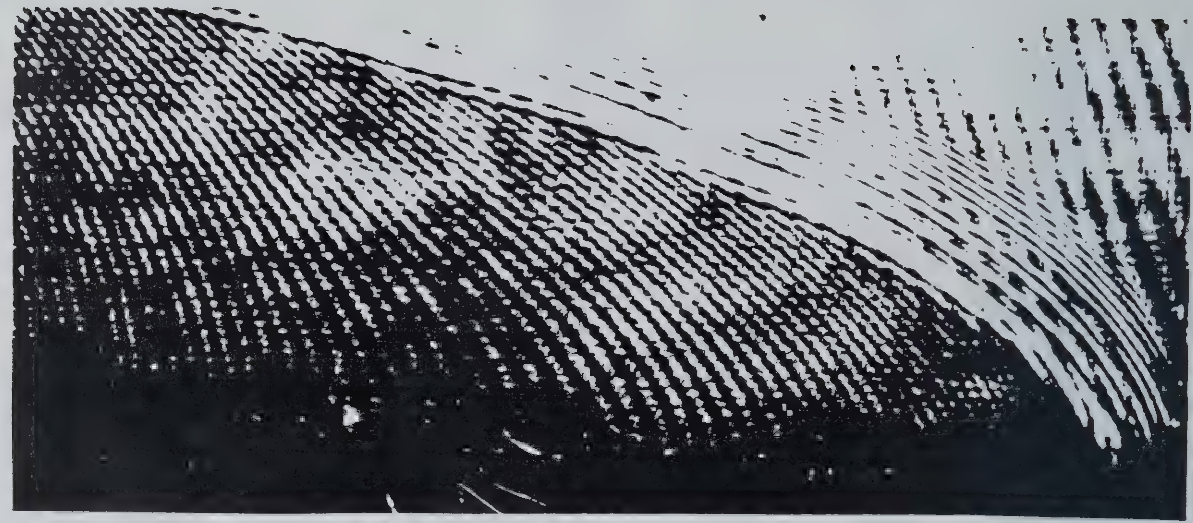
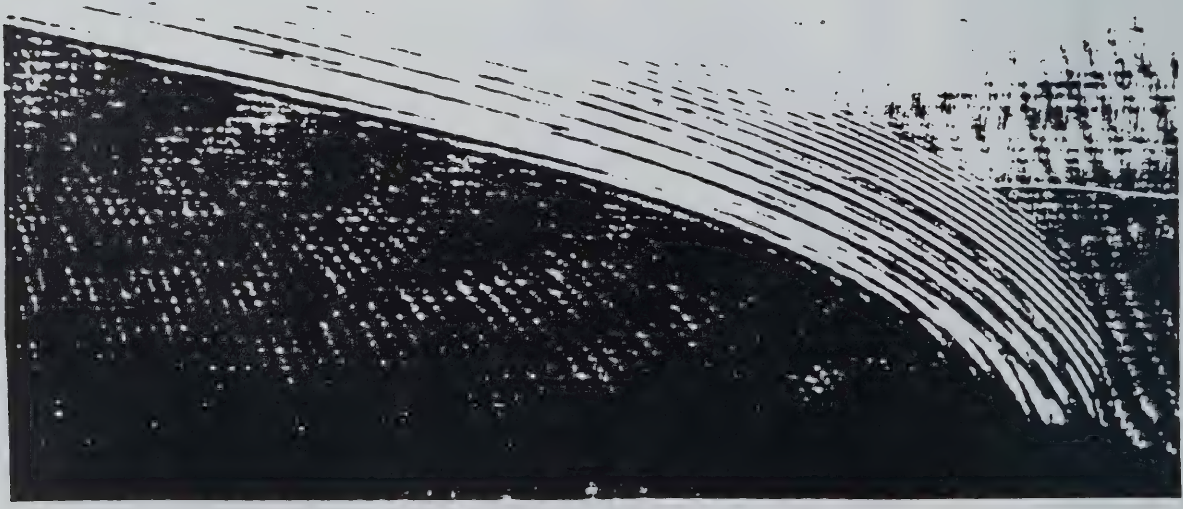

FLAME SPREAD RATE ON PMMA (mm/min)
MAIN FLOW VELOCITY (m/sec)
0
1
2
3
4
5
0
0.5
1.0
1.5
2.0
2.5
+ u'/U = 1%
□ u'/U = 5%
▽ u'/U = 10%
⋏ u'/U = 15%
▽ u'/U = 20%
⬠ u'/U = 25%

FIGURE 2.



3.a. $U_m = 0.2$ m/s $U'/U = 1\%$



3.b. $U_m = 0.5$ m/s $U'/U = 1\%$

FIGURE 3.

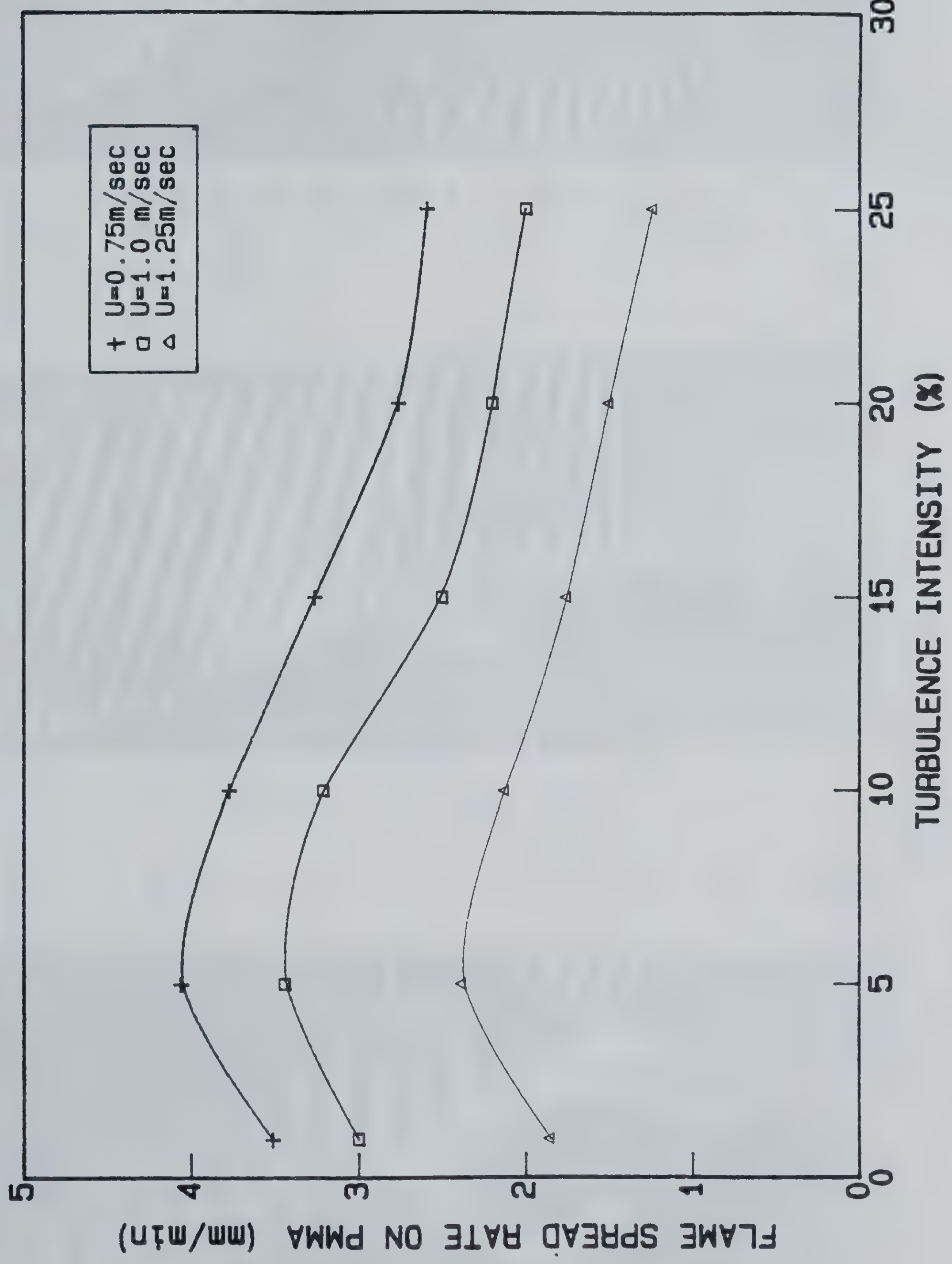
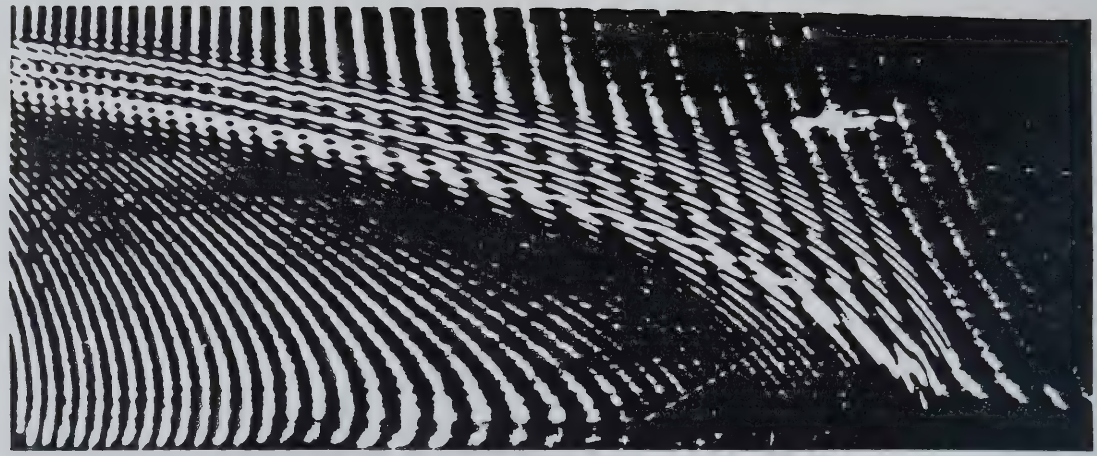
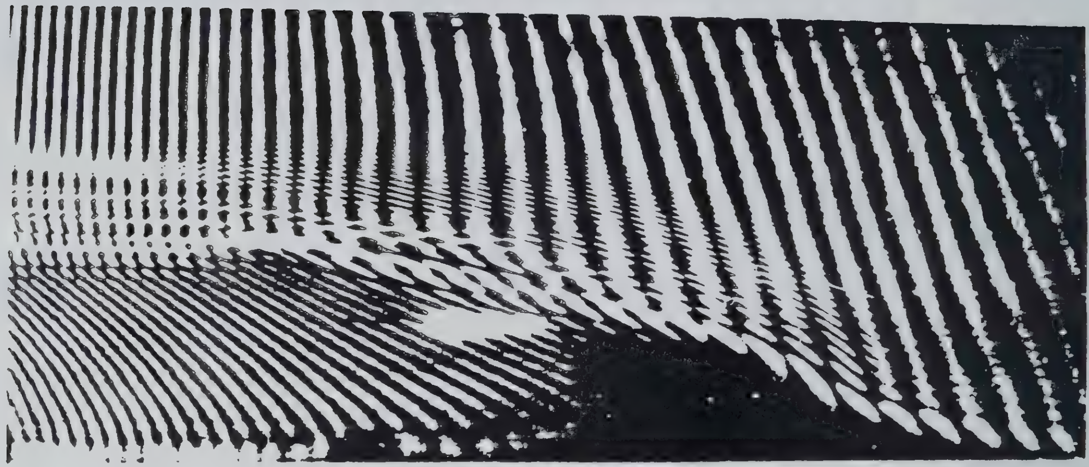

FLAME SPREAD RATE ON PMMA (mm/min)
TURBULENCE INTENSITY (%)
0
1
2
3
4
5
0
5
10
15
20
25
30
+ U=0.75m/sec
□ U=1.0 m/sec
△ U=1.25m/sec

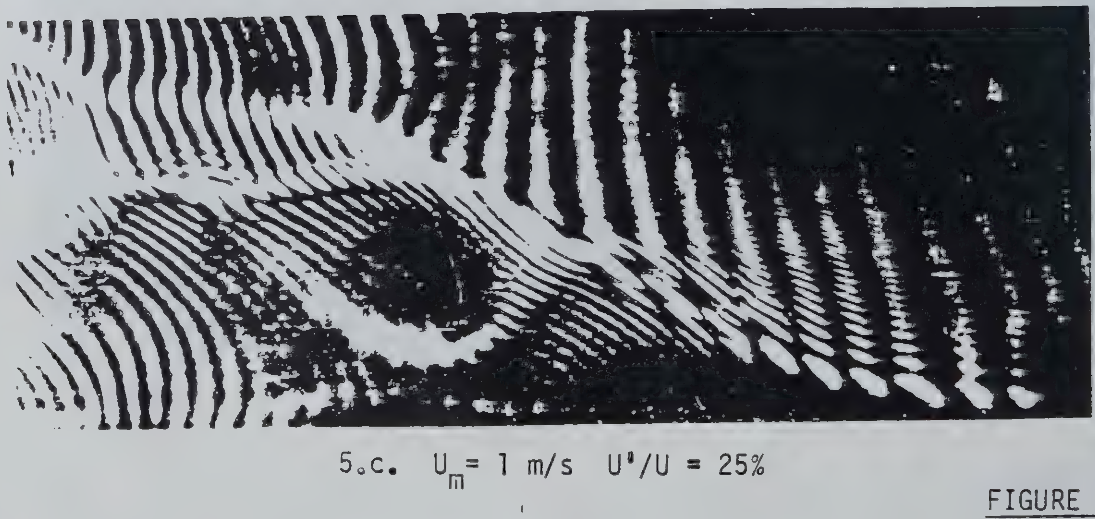
FIGURE 4.



5. a. U_m = 1 m/s U'/U = 1%



5. b. U_m = 1 m/s U'/U = 10%



5. c. U_m = 1 m/s U'/U = 25%

FIGURE 5.

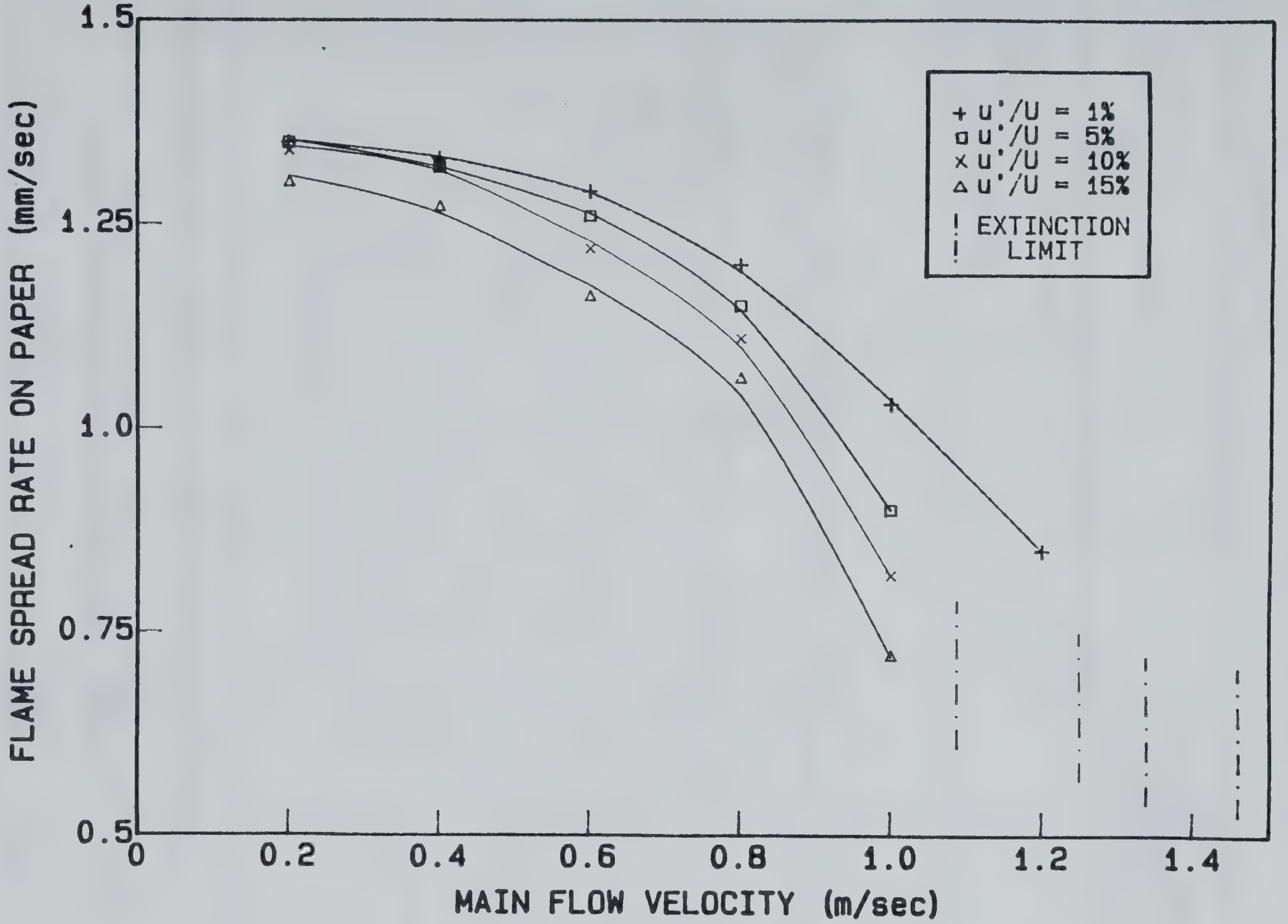

FLAME SPREAD RATE ON PAPER (mm/sec)
1.5
1.25
1.0
0.75
0.5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
MAIN FLOW VELOCITY (m/sec)
+ u'/U = 1%
□ u'/U = 5%
× u'/U = 10%
△ u'/U = 15%
EXTINCTION LIMIT

FIGURE 6.

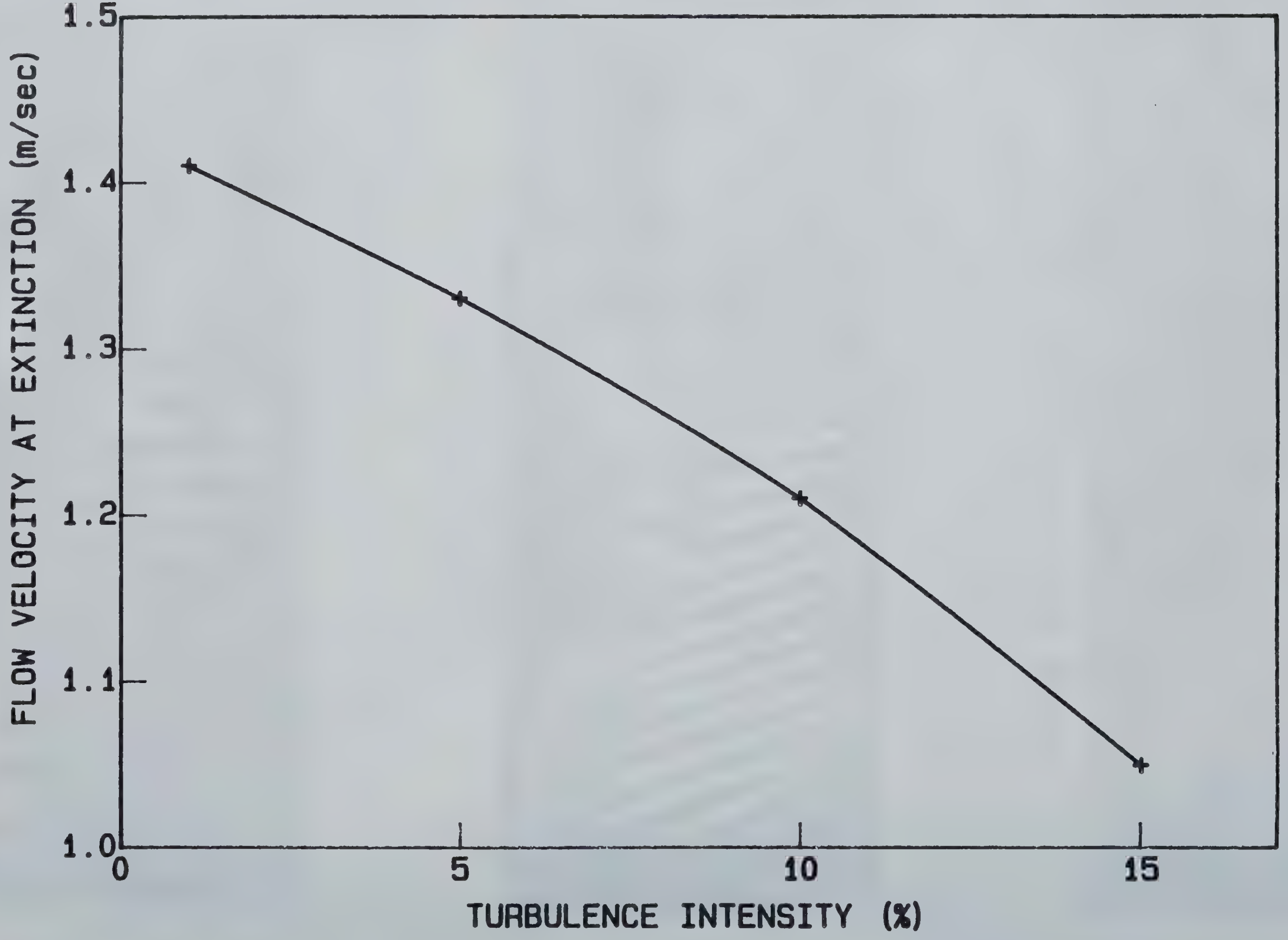

1.5
1.4
1.3
1.2
1.1
1.0
FLOW VELOCITY AT EXTINCTION (m/sec)
0
5
10
15
TURBULENCE INTENSITY (%)

FIGURE 7.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The research tasks completed during this reporting period include an experimental study of the effect on the spread of flames of the turbulence intensity of an opposed air flow, and a theoretical analysis of the concurrent spread of flames over thin fuels. Both studies are in our opinion important contributions in the study of the flame spread process. The results of the experimental study show that the flame spread process is significantly affected by the flow turbulence intensity for flames spreading over both thin and thick fuels. For a fixed flow velocity, the spread rate decreases as the turbulent intensity is increased. This appears to be due to the turbulent convective cooling of the fuel surface and gas in the vicinity of the flame front. Also observed is that extinction of the flames occurs at lower velocities as the turbulent intensity increases. The results of the theoretical analysis, which are in good agreement with previous experimental measurements, give detailed information about the flame structure and mechanisms of flame spread. It is shown that the flame length and consequently the rate of flame spread, are strongly dependent on the interaction between the pyrolysis and burn-out fronts.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

air flow; flame length; flame spread; poly(methyl methacrylate); pyrolysis

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